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THE MOVEMENT OF LOAD IN STREAMS OF VARIABLE FLOW.

BY

ROBERT MARSHALL BROWN.

The problem of the low-water stages in streams of variable flow is concerned with the use of the river as a highway. A highway for the products of the country, and especially for the staples of trade, must be open to traffic at the same time with competing lines. Untoward accidents, which are confined to one line of trade and which are so frequent as to cause a feeling of uncertainty concerning the possibilities of an uninterrupted transfer, operate against the business of any trade route. The low-water season of a navigable river may be a period of difficult, if not impossible, navigation. Apart from the chance that the amount of water may so decrease as not to yield a sufficient depth for navigation, there is generally a dissipation of the power to maintain a channel of a low-water stage because of the overloaded condition of the river during successive stages of fall. Oftentimes so rapid is the decline in stage that bars are formed which distribute the flow over extensive areas of shoals, and the low-water channel becomes annihilated. The deposition of detritus has been studied under various phases. Many methods of maintaining a low-water channel and counteracting the influence of bars and shoals have been tried. Three different methods are now in extensive use. Streams differ so widely in all the factors which influence the deposition of load that no one method is expected to be applicable with the same degree of efficiency to all streams. The presentation of the various factors in deposition of load may be found herein as well as the attendant results upon navigation, the regulation of streams, and the success in maintaining a navigable channel. As the measure of a stream's deposit is ordinarily given in terms of navigability, and the operations against the deposits are largely directed toward the maintenance of a highway, it seems advisable to include in this paper a statement, of such length as to do justice to the situation, of the works of regulation, in the belief that additional light may be thrown upon the problem of deposition of load.

Wave-like Movement.—The Mississippi River Commission during 1882 reported * on the movement of detritus. They hold, among other things:

That the bottom of the river is in an unstable condition and constantly in a state of motion;

That the bottom of the river consists of a series of transverse ridges approaching the form of waves under their most favourable development. These waves have an irregular motion down stream. Their maximum size and rate of progression agree in time with the river's highest stand. Their movement is fastest in mid-current and diminishes with the increase of distance from this channel. The waves have the minimum rate of progression and size at low water;

That the heavier material moved by a river is pushed up the up-stream side of a wave by the force of the current and rolls down the down-stream side. Here it remains until the wave has progressed down stream over it, when it is again exposed to the action of the current;

That the waves retain their form under uniform conditions of flow, but are obliterated by a sudden decrease of velocity of the river, because of the large increase in deposition of sediment.

The extreme conditions affecting the bed of a river would be realized under a moderate and uniform drop of the river from its flood stage to its normal low-water stage, and under a sudden drop of the river between these two stages. In the former change of stage the waves of sand would grow uniformly less in size, be more evenly distributed along the river, and, while their number might be increased, they would not, except at an abnormally low stage, block the channel of the river. Under the latter condition the decrease of velocity is sudden, and the detritus cannot assume a shape of deposit which has any suggestion of order, but is dumped in varying amounts along the river bed. The sediment, which under a slower decrease in stage would be widely distributed, upbuilds temporarily the bed of the stream and obstructs the flow. As a rule the bends of a river, because of the forced confinement of the flow, yielding a swifter current and a greater depth than is found in other parts of a stream, sweep clean their channels. The crossings and straight reaches receive heavy deposits of sediment; the river is spread over a wide and shallow lying bar at these places, and is no longer able to scour a channel.

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* Report of the Mississippi River Commission for the year June 30, 1882, p. 88.

UP-BUILDING OF BED.—The deposit found in a stream under low-water conditions is not permanent. The next flood stage starts the detritus down the stream. The tendency is that a stream under high-water conditions, because of its depth, will scour the bed deeper than under a more natural flow. The limit of scour is reached when the load which is rolled along the bottom begins to tax the transporting power of the river. A river under an irregular flow along a gradual slope cannot build up its bed. That a river does this thing has been used as an argument against the permanent protection of alluvial plains by embankments. The deposit under low-water stages does not concern in any direct way the constructors of levees; under a high-water stage there is little or no deposit, for the detritus is in motion. The striking feature of the flood of 1897 on the Mississippi River* was the greater height of the flood wave in the lower portions of the river than the stage at the upper river stations led the engineers and the riparian proprietors to expect. The proposition was established, furthermore, that this feature was not abnormal, but, on the contrary, such a change in the regimen of the river had taken place that any flood wave passing Red River Landing (765 miles below Cairo) at a high stage may be expected to cause a flood wave at Carrollton (950 miles below Cairo), a foot or more higher than a flood of the same height would have caused fifteen or twenty years ago. The explanation of this change in flood height has been that it resulted from the up-building of the river's bed, and in this particular case that the bed was filling about and below Carrollton. If such were the case, it is obvious that the effect in the instance of low flood waves would be proportionally more noticeable than in the case of the high. Tables of low flood waves show no tendency whatever towards an increase in the height of the low flood wave at Carrollton, and the theory of a filling channel must be abandoned. This conclusion is reached somewhat as follows. The floods which have been recorded since 1872 at Red River Landing and Carrollton, and having gauge readings at the former station of 22.3, 21.4 and 19.3 approximately, are tabulated. The ratio of the Carrollton stage to the Red River Landing stage is calculated in each instance. The ratios of the stages about 19.3 are found to be uniformly less than those of the other two stages, and, furthermore, the ratios have decreased somewhat during the later years. The argument is enforced by the discussion of other factors which may be instrumental in yielding the increasing flood stage at Carrollton. This feature may be the result of the closure of crevasses in the river below Red River Landing, but there is no evidence in support of this hypothesis. Certain conditions have increased the carrying capacity of the river above the stage of a moderate flood above Carrollton, and to this is due the increase in the high flood stage at Carrollton. The immediate result of an increased carrying capacity between Red River Landing and Carrollton was a distribution of the flood waters, and this was evidenced in a diminution of the high-water slope. This would not be felt at Carrollton in any such marked degree as at Red River Landing. At the latter station a lower stage would be recorded than under a similar flood a few years previous. It is not so much that the flood height has been increased at Carrollton as that it has been lowered at Red River Landing.

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* Report of the Mississippi River Commission for the year ending June 30, 1900, p. 4551.

The Rhine has been constrained by levees for a number of years, and no change in bed-height is noticeable. Conflicting reports reach us concerning the Po. Some rivers of Japan are reported to have raised their beds. These occur, however, on alluvial fans where protecting embankments have been built, until in some instances the river is forty feet above the plain. Harcourt says* that the railroads across these plains have been placed in tunnels on a level with the surrounding country and underneath the stream. Thus is avoided not only the inconvenience of floods, but also the constant demand for regulating the road-bed to the caprices of a shifting and up-building alluvial fan. The case of the Hoang-ho is similar. The levees were placed on an alluvial fan where the change of velocity of the mountain stream debouching onto the plain resulted in the aggradation of the river-bed. So, to revert to the Po, it may be found that where the river and its tributaries leave the Alpine slopes for the lesser slopes of the plains of Piedmont and Lombardy, if constrained by levees, a rising of the river-bed must result. When the river has passed completely beyond the bounds of the condition favourable to fan formation, the detritus is probably transported, as in other streams of gentle slope and irregular flow.

SCOUR AND FILL SURVEY.—Covering a period of fifteen months, a board called the Scour and Fill Survey† ascertained by many soundings the nature and extent of the changes occurring in the bed of the Mississippi River within a limited area. Their findings are here briefly summarized. The location of the work was a bend and a reach heading at New Madrid, Missouri, and extending downstream for about six miles. The stretch was divided into its pool and crossing sections, and sections intermediate between the two. The record gives us data for low-water stages and medium-water stages. A high-water stage did not occur during the interval of the board's existence. In the low-water stage the pool sections showed a tendency to fill during the earlier part of the rise of water during the season of observation, the cross-sections at high-water stages being only slightly larger in area than those of the low-water stages. The crossing sections showed opposite tendencies. On a rising stage these sections showed a scour; and a fill on a falling stage. During the intermediate stages it was noticed that the width of the pool sections was increased proportionally much more than the areas, and that the mean depth was decreased. The character of these sections was changed by extending them over the wide sand bars. Therefore the sections under this stage were considered in the same class, and the result was the same as for crossing sections. The results of the observations at this point showed that beginning with low water, and extending through a period of moderate high water, the pool sections decreased slightly, and the bar sections increased slightly in area. Secondary rises in a river tend to rearrange the detritus deposited during the general fall in stage and set it in motion again. Such rises are, then, favourable to the maintenance of a navigable channel so long as the rising stage continues. When this ceases and the fall of the river begins, a second deposition of the load takes place. The more gradual the decline in stage, the better is the distribution of the load along the bed, and navigation is therefore less likely to suffer. As far as can be discovered, advantageous conditions during a rising stage presage nothing concerning the conditions during the subsequent fall in the stage.

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* Harcourt, L. F. Vernon. Rivers and Canals. Vol. I., p. 167.

† Report of the Mississippi River Commission for the year ending June 30, 1901. 128.

REGULATION OF LOW-WATER CHANNELS.—Works of regulation are not necessarily connected with the detritus of a river, but in most cases they have some relationship to it. The necessity of regulation, if the river is to be a highway, arises, first, from the lowering of the river stage during the drier seasons of the year; and, secondly, from the temporary up-building of the bed, due to the lessening capacity of the river for sediment during its decrease in stage. Under our title, the first factor always obtains; the second may or may not be active in an appreciable degree. A river varies from year to year in the openness of its low-water channel. The condition of one year is no sign or promise of what the channel may be in succeeding years. A year may pass when the river is open to navigation with no regulation. This may be the result of a slow decrease in stage during the summer and fall, or of favourable rises of the river during the low-water season. Again, a year may be marked by continual and persistent deposition, so that the efforts to keep the channel open are unavailing. English engineers consider it sufficient to regulate a low-water channel in reference to normal low water. Excessive low water is so infrequent, and works of regulation are so expensive, that the outlay during extreme stages does not seem consistent with the broadest management. In the case of any river, such a policy during the first years of the work may be detrimental to the plans by discouraging shipping or blocking legislative appropriations, unless navigators, engineers, and shippers agree on what constitutes abnormal low water for the river in question.

Three methods are extensively used for regulating a low-water channel—confinement of channel, canalization, and dredging.

REGULATION BY CONFINEMENT.—For a number of years previous to 1897 a plan was projected to confine the Mississippi River during the low-water season between levees 3,000 feet apart. Considerable uncertainty existed concerning the feasibility of the plan. The opinion which prevailed was against such a procedure, on the ground that the low-water channel does not necessarily agree with the high-water channel, and this disparity of current-location would probably make the low-water levees a focal point of large deposition, which could not be removed during the falling stages. Portions of the Rhine River have been opened for commerce by such means. The Rhone * has the disadvantage of a strong current, so that the up-stream navigation is carried on with considerable difficulty. Between Lyons and the sea, training levees have confined the waters during low-water stages and thereby decreased the deposit of sand-bars. Some German rivers, notably the Elbe, are other examples of the regulation of the low-water stage by confinement levees. This method does not yield in the cases cited a depth of more than six feet throughout the length of the regulated water-way. If the low-water levees are so located as to maintain a steady flow of water during the drier season, the detritus is kept in motion, and is thereby nearly eliminated as a factor. Then the possibilities of navigation hinge almost entirely on water volume.

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* For my data concerning European rivers, I have drawn upon Harcourt, *opus cit.*

Regulation by Canalization.—The canalization of rivers has been more successful than confinement in improving low-water navigation. By this method the flow of water is practically stopped and navigation is equally easy up or down stream. The use of locks and dams in rivers of slight slope, where the disparity of width between the high- and low-water stages is not great, is less expensive than continuous training works. On the Seine there are locks 13½ miles apart, and this yields a depth of 10½ feet—1½ feet deeper than is considered necessary on the Mississippi River. The Main, a tributary of the Rhine, has been tried by both methods, and the regulation by confinement was abandoned in favour of canalization. In the former case less than a three-foot channel was realized; a six-foot channel was obtained by the aid of locks. The tonnage of traffic under training-works and under canalization was as 1 to 25. This method of regulation is also in use in the United States. In a canalized stream the stoppage of flow is beneficial to navigation on the whole. Furthermore, the retention of the waters by dams promises a more constant waterway than that under confinement levees. However, when traffic is heavy there will be a considerable drain of the water supply, and, during a low-water stage, this loss of water is liable to become serious. In the rivers above mentioned the amounts of sediment transported are not large. Notwithstanding, some dredging has been done in the Seine. The effect which locks and dams would have in a river carrying a large amount of sediment is problematical. That the detritus would impair the efficiency of such regulation is obvious.

Regulation by Dredging.—This method of regulation is a direct attack upon the deposits, and is the one in operation on the Mississippi River. As some idea of the amount of deposits and their distribution may be gained from the work of the dredging parties, the experiences and operations during the dredging season on this river are dwelt upon to some length.

The immediate result hoped for in the dredging project is a channel from Cairo to the Gulf, with a width of 250 feet and a depth not falling below 9 feet throughout the year. In order that this may be accomplished, rapid surveys must be undertaken from the beginning of the flood decline, especially at such localities where shoaling is expected, so that the dredges may begin the work of deepening and widening while the conditions are still in excess of the minimum needs. In the carrying out of the plan, the greatest responsibility rests on the engineer who locates a channel through a shoaling area. This location, to be successful, must be the path which the river will take during its low stage. To infer this path during a falling stage is not always possible. There may be more than one locality where a channel, opened, would lead the current of the river; but this, furthermore, is in the project—namely, that the channel be at least maintained, if not improved. A channel with a developing tendency towards crookedness offers an uncertain pathway for steamers; consequently an effort is made to keep the cuts as straight as possible. While in the main the channels are confined to the cuts prepared for them, there arise instances, here and there, where the tendency during a certain stage gives little promise of what it will be at a lower stage. At Corona Crossing last year (1905), after some uncertainty, a channel was located and dredged. The selection of the location proved to have been unwarranted and the location was abandoned, and a second location selected and dredged. This latter cut appeared to be successful, as far as the required depth of water was concerned, and there was considerable promise of its maintenance by the river. Unfortunately, it was located in such a way that it led steamers passing through it too near a bar, and was, therefore, abandoned. A third channel was dredged with eminent success. Even in this instance there seemed to be a feeling that this last location could have been made at the beginning, if the study of the silting processes had been properly interpreted. A few instances are recorded where a channel was opened and never used, as the river made another. At New Haven, in 1905, the channel followed the concave shore. As shoaling was feared on account of the caving, a new channel was dredged away from the shore. All the while the shore channel improved, and, as the steamers found that it was easier to run, the new channel was never used.

The magnitude of the work may be apprehended by a review of the operations at one or two localities of continual dredging. These indicate areas not only of large deposits, but also of a dissipation of stream power, so that there is a failure to maintain a channel, one factor being a concomitant of the other.

The range from Darnells Crossing to Bixby Towhead and Point Pleasant has been a troublesome spot. This locality is five miles below New Madrid. The river as it approaches this place broadens, and at Darnells Point the river bifurcates. For seven years this two-mile stretch of river has given considerably more than the average amount of trouble. During 1899 it was considered the most difficult of all places for the year. An attempt was made to regulate the channel by fixing the flow by dikes. The dikes were intended to check the caving of the banks and bars and to close one of the channels of the river, the one to the left of Bixby Towhead. It was expected that these dikes would turn the waters of the river to the right channel, and that the narrowing caused thereby would be instrumental in making and maintaining a straight channel. The results of the work were not entirely satisfactory. The dikes failed to secure a channel. A channel had to be dredged to assist the dikes; even then the cut was not what was desired, being crooked, narrow, and hard to run. During 1900 this locality is again rated as the most difficult of any for the season. Much of the dike system had been destroyed by the preceding high water, but, somewhat in compensation, the river had taken the desired path, and, after some dredging, maintained a way through the cut. During 1901 no dredging was necessary at this place. During 1902, however, the previous record of the station was equalled, and more work was done at this locality than at any other station during the season. The hydrograph for 1902 shows two very definite rises of the river, one in September and another in October. The fall in stage in each case filled the channels with sediment. In general the river here was broad, and the channel unstable and shallow. Although the low-water season of 1903 was marked by an almost clear channel until December, the records indicate trouble from the apathy that resulted from lack of work. Dredging was carried on at the Towhead during August, September, and October, mostly during a too high stage of the river, in anticipation of trouble. The work was not effective, and the dredging was continued through November. When low water did come on December 5, the long waiting for work found the operatives unprepared, and the season was closed under unsatisfactory conditions. At Darnells Crossing, while dredging was needed on December 10, no dredge was ready, although they were not in use, until the 28th. A little dredging was done at the close of the year, but the winter rise came to the relief of the dredges and ended the season. During 1904 considerable dredging is recorded at this station.

Another condition is illustrated by the results at Hathaways Crossing and Island Number 40 Crossing. The former is a broadening of the river below a bend, and acts somewhat as a lake in catching detritus. The latter is near a separation of the channel caused by Island Number 40 or Beef Island. Hathaways Crossing was, previous to 1899, one of the most difficult to cut and maintain. During 1899 and 1900, neither of these crossings demanded dredging. This freedom from trouble was considered a resultant of the previous season's work, and the belief was current that "where no radical change takes place in the river, and where a dredged cut fills up during the high-water season, this filling is looser and less compact than at other places on the crossing, and that the river during subsequent low-water periods finds it easier to make its way through these cuts than elsewhere across the bars." In the years subsequent, the Beef Island Crossing has given no further trouble. Hathaways was dredged three different times during 1901, was considered second in point of troublesomeness during 1902, and was dredged continually during 1903. During 1904, it gave no trouble. There seems to be little hope that a season's dredging will result in a better channel during a subsequent year. The two cases above cited seem to be over-emphasized, the only instances of the kind during seven years. As far as Beef Island is concerned, the tendency of the river was to flow through Beef Island Chute to the exclusion of the wider and troublesome crossing. This chute is narrow, and as soon as a proper amount of water flowed through it the confinement of the water was instrumental in holding a channel.

The amount of dredging depends on the length of the low-water season and whether the season is broken by secondary rises. Any hope that there may be a relief from dredging must be shattered when the records of the seasons are studied. In the 1904 dredging season, more dredging was done than during any of the previous seasons; during this season more dredging was done than during 1902 and 1903 combined. This may be accounted for by the length of the season. Medium low-water stages were recorded earlier and lasted longer than for any other year of the dredging operations. The number of hours of dredging was twice that for 1903 and 30 per cent. greater than for any previous year.

LOCATION OF DEPOSITS.—Deposits occur in a meandering river at the ends (toe-caps) and the down-stream side (scrolls) of lobes. Where a river does not meander, the current crosses and re-crosses the river and there is developed a cutting, a filling and a crossing action comparable to the more strongly-marked features of the meander. Especially where cut-offs have occurred this cutting and filling action is prominent for many miles above and below the location of the abandoned meander. The process of widening the meander belt by the cutting and the consequent filling on the opposite shore along the pathway of the withdrawing stream is not of any considerable moment to navigation. In these localities the river maintains a navigable depth as long as the stage permits navigation. It was found in the Brazos River in Texas* that the average width of bends in the river was 7½ per cent. less than in the reaches, while the average cross-section in bends was 13½ per cent. greater, making the average maximum depth in bends 58 per cent. greater than in reaches. The deposits of the toe-cap and scroll varieties are not, then, essentially a hindrance to navigation. In the same class would fall the fills subsequent to cut-offs. It is in the crossing sections that trouble arises. During the last seven years of dredging on the Mississippi River there appear to be eight stretches where considerable work was demanded. These may be placed in three categories—namely, resultants from cut-offs, separation of stream, and widening of stream. The instability following the precipitation of a cut-off is felt over a greater reach of river than is the experience under the other two causes. In the case of Commerce cut-off, twenty-five miles of the river are now of uncertain navigable quality; while in the Centennial cut-off region, fifteen miles are in a similar condition. The Needham's cut-off region, with a seven-mile stretch, because of the time elapsing since the cut-off occurred, is placed in another category. After a cut-off has occurred the process of cutting and filling which results increases the number of crossings above and below the abandoned meander. In this increase in the number of crossings may lie a reason for the large amount of deposit during a falling stage of the river. The widening of the stream and the separation of a stream by an island are not necessarily of different origin. The one state may be a later stage of the other. The river as it leaves a pool-section in four or five instances on the Mississippi River increases in width from half a mile in the bend to two miles a short distance below. The Gold Dust Crossing is a good type of this thing. It in its most troublesome section contains islands also. It was here that experimental dikes † were constructed to shut the river out of one of the channels, thereby lessening the width of flow, in the hope that the river would maintain a cut in the other channel. The experiment was not considered a success, although the conditions were ameliorated for the time being in one or more localities. Stretches of river of eight miles and less, with dredging demands for every mile and in each instance a broadening of the river to three times its width where it leaves the pool section, make up the remaining six dredging sections.

The prediction of localities of filling is not difficult. Most conditions of deposition are definite enough to arouse suspicion. Success in maintaining a navigable channel does not rest on the foretelling of locations where trouble is likely to ensue. It rests on locating the place where the river is most likely to maintain a channel through the detritus. This can only be known by carefully watching the tendency of the stream as it moves over the shoal during all its time of falling stage. Even then there is always the chance that the quantity of water may fall short of the minimum demands for navigation.

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* Tidal Rivers. W. H. Wheeler. 1893, 56.

† See Report of the Mississippi Commission for the year ending June 30, 1901, 235, 245.

WORCESTER, MASSACHUSETTS.

THE ASCENT OF RUWENZORI.

The Duke of the Abruzzi lectured on Jan. 12 before the Royal Geographical Society of London on his recent expedition to the Ruwenzori range. King Edward VII was present. This was the first occasion on which a reigning British monarch had attended a session of the Society, though as Prince of Wales the present King had frequently been at the meetings. One of the fine photographs with which the Duke illustrated his paper in the *Geographical Journal* (Feb., 1907) is here reproduced. It shows some of the highest mountains which constitute the culminating portion of the Ruwenzori range.

At the outset the party lost the services of Captain Cagni, who was to have charge of the magnetic observations. Unfortunately, he was attacked with typhoid fever before reaching the mountains. Lieutenant Winspeare, who was to direct the meteorological and topographical observations, was also incapacitated by illness. The Duke's assistants included Dr. Major Cavalli Molinelli, physician, zoologist, and botanist; Signor Sella, photographer; Dr. Roccati, geologist; two Alpine guides and two head porters from Switzerland, an assistant photographer, a cook, and about 200 Waganda porters.

The neighbourhood of the mountains was reached on June 1, and about seven weeks were given to mountain-climbing, exploration, and surveying. The failure of previous attempts to reach the culminating points of this range may be attributed to the lack of mountaineering experience. The expert snow-climbers in the Abruzzi party had no difficulty in their ascents either on rock or ice, and the snow was always in good condition. The Duke has